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PILOT IRRADIATION OF AMERICIUM

INTRODUCTION

Mixed Am oxides, which will be available from power reactors in the next decade, provide suitable target materials for the production of medical grade ^{238}Pu (<0.3 ppm ^{236}Pu contaminant) from ^{241}Am and for the production of target material (^{243}Am, ^{244}Cm, ^{245}Cm) for a subsequent high-flux irradiation to yield ^{252}Cf. A pilot irradiation of Am isotopes is planned in order to demonstrate fabrication and irradiation capabilities at SRP.

Originally it was planned to irradiate a mixture of Am oxides, from Hanford, containing 465 gm. ^{241}Am, 2 gm. ^{242m}Am, and 133 gm. ^{243}Am, in a single quatrefoil replacing a Mark 30 target in Gang III of a

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Mark 14-30 load. Subsequently an additional 2000 gm. ^{241}Am became available from ORNL, so that later plans envisioned the irradiation of the entire 2600 gm. Am isotopes in either two or three quatrefoils, replacing as many Mark 30 targets in Gang I of the E-D load. Currently it is planned to irradiate the Am in four quatrefoils, replacing as many Mark 30 targets in Gang I.

The investigation described here was carried out to predict the reactivity changes, power peaking, etc. caused by the substitution of Am assemblies for targets, and to estimate the amounts of desired isotopes which could be produced.

SUMMARY

2.6 kg of Am can be irradiated satisfactorily in two to four quatrefoils, replacing as many Mark 30 targets in Gang I of an E-D load. Use of four quatrefoils is preferable in order that power generation in the Am assemblies be kept within acceptable limits.

Production of the desired isotopes is insensitive to the stage in a fuel cycle at which the Am irradiation is started. The ultimate yield of $^{238}Pu + ^{242}Cm$ is 1067 gms, after exposure for six target stages; at this point, 82% of the ^{241}Am has been burned up, and the $^{238}Pu + ^{242}Cm$ content is only slowly increasing.

The reactivity increase resulting from the displacement of targets by lighter Am assemblies is a maximum at the start of stage 1. The effect is greatest for four quatrefoils (as much as + 0.0107 at the second start stage 1 if the irradiation is started five target stages earlier), less for three quatrefoils, and still less for two quatrefoils. Power peaking in adjacent Mark 14 drivers is also greatest at the start of stage 1, where with no control rod trim, it could reach 85% for four quatrefoils at start stage 1 after irradiation of the Am for five target stages. Both Δk and peaking are greater at a later rather than an earlier start stage 1, because the partially burned up Am assemblies, now lighter than originally, still replace fresh targets. Peaking can be reduced to acceptable levels by adding control rod trim - which also reduces Δk.

Power generation in the quatrefoils increases with exposure because of the buildup of fissionable isotopes in the Am. For a nominal driver power of 7 MW/Mark 14 assembly, the maximum fission power generated in an Am assembly during the four-quatrefoil irradiation is 1.06 MW/quatrefoil with added trim. If γ heating is included, the corresponding maximum sensible power is 1.26 MW/quatrefoil. This is within acceptable limits.(6) Current plans call for the irradiation of Am in four quatrefoils as follows:

632 gm. mixed Am isotopes from Hanford (as 794 gm. oxide) will be made into 72 six-inch slugs and irradiated in a single quatrefoil in four nine-foot columns of 18 slugs each. 2001 gm. ^{241}Am from ORNL (as 2326 gm. oxide) will be made into 216 six-inch slugs and irradiated in three quatrefoils, each containing four nine-foot columns of 18 slugs each. A suggested charging pattern is included (Fig. 2).

DISCUSSION

1. Background

Mixtures of ^{241}Am and ^{243}Am will be produced in power reactor fuel and are expected to be the principal source material for a large-scale ^{252}Cf production program. The ^{241}Am is a "contaminant" that does not contribute significantly to Cf production. Its irradiation does yield ^{242}Cm, however (see Fig. 1), which decays with a 163 day half-life to ^{238}Pu. Thus, ^{238}Pu would be a valuable byproduct of a Cf production program. ^{238}Pu made in this way, rather than by irradiation of ^{237}Np, has a special virture of very low (probably < 0.3 ppm) ^{236}Pu contamination, which makes it suitable for anticipated medical applications.

Irradiation of the 241/243 mixture was proposed as a demonstration of the procedure now envisioned for irradiating power reactor americium to make Cf feed materials plus byproduct ^{238}Pu. The principal reactions involved are illustrated in Fig. 1.

Irradiation of 2 kg of pure ^{241}Am was proposed later for the purpose of providing a larger quantity of "medical grade" ^{238}Pu.

The original plan to irradiate the 600 gm. mixture in a single quatrefoil was revised when the 2 kg of ^{241}Am was included. For this case two alternatives were entertained, viz., either 2 or 3 quatrefoils, each containing four 12-foot columns (96 six-inch slugs per quatrefoil). Detailed calculations were carried for both alternatives.

One of the results derived was that the maximum quatrefoil power would be higher than recommended by Reactor Engineering Division.(6) This prompted revising the configuration to four quatrefoils, each containing four 9-foot columns (72 six-inch slugs per quatrefoil). Some, but not all, of the detailed calculations were repeated for the four quatrefoil case.

The several reactor locations considered in the detailed calculations are shown in Fig. 2. Recommended positions for the final proposal of four quatrefoils are included.

2. Method of Calculation

The effects of replacing Mark 30 targets by Am assemblies were calculated by JPROD.HERESY using cell average parameters calculated by HAMMER, except that GAUGE was used for four-quatrefoil cases in which the lack of symmetry forced a 360° reactor calculation. Isotopic changes with exposure were calculated with APE.

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The HAMMER runs used the newly-available[2] cross-sections for ^{241}Am, ^{242m}Am, ^{243}Am, ^{242}Cm, ^{244}Cm, and ^{245}Cm.

In APE, the ratio of the thermal (0-0.625 ev) to 2200 m/sec. cross-sections $\sigma^a_{th}/\sigma^a_{2200}$ and $\sigma^f_{th}/\sigma^f_{2200}$ were taken as quadratic functions of ϕ_{epi}/ϕ_{th}; the coefficients a_o, a_1, a_2 of these relations were computed to yield σ^a_{th} and σ^f_{th} values in agreement with those of THERMOS, with APE input values of σ^a_{2200} and σ^f_{2200} set equal to the HAMMER thermal library (LITHE) values.[2,3] For some isotopes, e.g., ^{238}Pu, LITHE values of σ^a_{2200} and σ^f_{2200} had to be adjusted for use as APE input, because APE assigns values of a_o, a_1, a_2 appropriated to $\frac{1}{v}$ isotopes (i.e., ^{238}Pu is not one of the isotopes for which a_o, a_1, a_2 can be read in directly); in this way the best average agreement with THERMOS values of σ^a_{th} and σ^f_{th} over the expected range of ϕ_{epi}/ϕ_{th} values is obtained. In the case of ^{239}Pu, LITHE values of σ^a_{2200} and σ^f_{2200} were also adjusted for use as APE input, because APE uses the same a_o, a_1, a_2 values for both ^{241}Am and ^{239}Pu; and while there is not a great difference between $\sigma^a_{th}/\sigma^a_{2200}$ for ^{239}Pu and ^{241}Am, it is more important that a_o, a_1, a_2 be given values appropriate to ^{241}Am rather than ^{239}Pu, which then necessitates some adjustment in σ^a_{2200} for ^{239}Pu in order that the APE average value of σ^a_{th} will agree with the THERMOS σ^a_{th} over the expected range of ϕ_{epi}/ϕ_{th} values.

For the fast contribution to the reaction rate, APE expresses σ_{epi}/I_{eff} as another quadratic function of ϕ_{epi}/ϕ_{th}, whose coefficients are nearly the same for all nuclides in a given assembly. These coefficients were calculated specifically for the Am assembly, rather than using coefficients built into APE for U or Pu fuel. Newer values[2] of the infinite resonance absorption integral and epithermal fission/epithermal absorption ratio were substituted for the APE built-in values for ^{241}Am, ^{242}Am, ^{242m}Am, ^{243}Am, ^{244}Cm, ^{246}Cm, ^{247}Cm, and ^{248}Cm; currently revised built-in values[4] were retained for ^{245}Cm.

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Flattened base-case (no Am assemblies) JPROD.HERESY data were already available*, based on HAMMER calculations for Mark 14 and Mark 30 assemblies, septifoils, etc. at the start of both stage 1 and stage 4. Modification of the initial base case was effected by use of a HAMMER-geometry mockup of a four-tube quatrefoil,[1] in which the entire 2600 gm. of Am was homogenized and uniformly distributed among the two or three quatrefoils. The Am composition at the start of stage 4 was computed by APE for both two and three Q-foils, assuming reasonable variations in ϕ_{th} and ϕ_{epi}/ϕ_{th} with exposure ($\int \phi dt$) in the Am; quatrefoil HAMMER parameters were recomputed, JPROD.HERESY re-run, the ϕ_{th} and ϕ_{epi}/ϕ_{th} functions corrected, and the entire process iterated until assumed and derived ϕ_{th} and ϕ_{epi}/ϕ_{th} functions agreed.

3. Reactivity Effects

The increase in lattice reactivity caused by the replacement of strongly-absorbing Mark 30 targets in Gang I by an equal number of less-strongly-absorbing Am assemblies containing a total of 2.6 kg of Am isotopes is shown in Table I. For three quatrefoils, Δk is simply the final JPROD.HERESY k_{eff} less the base case k_{eff}; for two quatrefoils, Δk is taken as 2/3 of the Δk computed for 120° symmetry. The four-quatrefoil Δk was obtained from GAUGE runs with the 360° lattice.

Table I

Δk for 2.6 kg Am Isotopes

Fuel Cycle	Am in 2 Q-foils	Am 3 Q-foils	Am in 4 Q-foils
initially, at start stage 1	+0.0012	+0.0025	+0.0046
after 3 target stages, start stage 4	+0.0003	+0.0013	-
after 5 target stages, start stage 1[a]	-	-	+0.0107

[a] If the irradiation is started at stage 4, two fuel cycles previously.

*From T. C. Gorrell; flattened base-case GAUGE data were obtained from H. R. Reeve for the start of stage 1 only.

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The reactivity increase is greatest for four quatrefoils, because four more strongly absorbing targets are being replaced by less strongly absorbing Am assemblies, rather than only two or three. The Δk is highest at start stage 1 where heavier Mark 30A targets are being replaced, rather than lighter Mark 30C or Mark 30D targets. If the irradiation is begun at stage 4 and continued for six target stages, the maximum Δk will occur at the second start stage 1, because the Am has been exposed for five target stages but still replaces fresh targets. Even in this case, the maximum $\Delta k = +0.0107$ (equivalent to a ΔB^2 of about 56 μB) can be reduced to +0.0034, +0.0006, or -0.0019 by adding one or two 3.2S or one 14.4S control rods, respectively, to each of the seven central septifoils. Hence no margin-of-control problems should arise.

4. Power Peaking

When a target is replaced by an Am assembly of lower Σ_a, the power in nearby drivers is increased. Table II shows the ratio of the power generated in drivers adjacent to an Am assembly to the average power generated in all Gang I and II drivers. These ratios were computed by JPROD.HERESY for a total of 2.6 kg Am isotopes (assumed homogenized) distributed among either two or three quatrefoils, for both fresh and partially-burned Am.

Table II

Power Peaking in Adjacent Drivers (No Trim)

Fuel Cycle	M14 Driver at	2.6 kg Am isotopes in 2 Q-foils*	3 Q-foils**
start stage 1	X29, Y57	1.18	1.27
start stage 1	X31, Y57	1.14	1.23
start stage 1	X31, Y51	1.20	1.31
start stage 4	X29, Y57	1.09	1.16
start stage 4	X31, Y57	1.04	1.10
start stage 4	X31, Y51	1.12	1.20

*at (X30, Y54) and (X26, Y42)
**at (X30, Y54), (X24, Y48), and (X30, Y42)

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This peaking can be reduced by relocating the Am in three quatrefoils to positions (X34, Y60), (X19, Y51), and (X31, Y33) next to sparjets which have replaced drivers and around which, therefore, the flux is already somewhat depressed. Peaking can be still further reduced by increasing the control rod complement in each of the two septifoils closest to each Am assembly, viz., at (X31, Y63) and (X36, Y60); at (X18, Y54) and (X19, Y45); and at (X30, Y30) and (X34, Y36). Table III shows the resultant power peaking in the two drivers closest to one of these Am assemblies (X34, Y60), as computed* by JPROD.HERESY, for the worst case (fresh Am).

Table III

Three-Quatrefoil Power Peaking at Start Stage 1
(2.6 kg Am in 3 Q-foils near sparjets)

Condition	Peaking in Driver at X33, Y63	Peaking in Driver at X35, Y63
Base case: no Am in lattice	0.99	0.95
With Am but no trim	1.21	1.17
With Am + one 3.2S rod added to nearest S-foil†	1.17	1.10
With Am + one 3.2S rod added to each S-foil††	1.10	1.08
With Am + one 14.4S rod added to each S-foil††	1.06	1.04

†at (X36, Y60)
††at (X36, Y60) and (X31, Y63)

In the last case listed above, the maximum power is generated in a driver in the central hex, i.e., at (X30, Y48), rather than in a driver adjacent to the Am assembly.

*Courtesy P. L. Ames

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Power peaking can be trimmed to acceptable levels, as shown in the above table. However, the total power generation in an Am assembly is high enough (see Section 5) that it is advisable to irradiate the 2.6 kg Am isotopes in four rather than three quatrefoils. Present plans[5] call for the irradiation of 631.7 gm mixed Am isotopes from Hanford* in four 9-foot columns (72 six-inch slugs) in a single quatrefoil replacing a target as centrally located as possible at (X29, Y51); and 2000.9 gm. ^{241}Am from ORNL in three quatrefoils replacing targets symmetrically located at (X25, Y39), (X25, Y57), and (X34, Y48), each of these quatrefoils containing four 9-foot columns (i.e., 216 six-inch slugs containing ^{241}Am), for a total of 288 slugs in all four quatrefoils.

Table IV shows power peaking in the drivers in the central seven hexes, calculated by GAUGE for fresh Am, with varying degrees of trim obtained by adding control rods to each of the seven central septifoils as indicated. Maximum peaking values are encircled; with the indicated trim, the flux is depressed in the center of the reactor and the maximum power peaks occur in Gang III.

*rather than the formerly expected 600 gm, according to Hanford documentation

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Table IV

Four Quatrefoil Power Peaking at Start Stage 1
(2632.6 gm. fresh Am in 4 Q-foils near center)

M14 Driver at X	Y	In Cluster	No Am	Am, no trim	Am with one added 3.2S	Am with two added 3.2S	Am with one added 14.4S
27	45	1	1.01	1.29	0.96	0.80	0.61
27	51	1	1.01	1.44	1.06	0.89	0.68
30	48	1	1.01	1.47	1.08	0.90	0.69
32	42	3	1.01	1.18	0.95	0.84	0.70
32	48	3	1.01	1.42	1.09	0.93	0.73
35	45	3	1.00	1.26	1.08	0.99	0.87
28	36	4	1.00	1.10	0.95	0.88	0.78
28	42	4	1.01	1.24	0.94	0.80	0.63
31	39	4	1.00	1.12	0.93	0.83	0.71
23	45	5	1.01	1.15	0.93	0.82	0.69
26	42	5	1.01	1.30	1.01	0.86	0.69
23	39	5	1.00	1.20	1.04	0.96	0.85
22	54	6	1.00	1.13	0.97	0.89	0.79
25	51	6	1.01	1.29	0.98	0.83	0.65
22	48	6	1.01	1.12	0.93	0.83	0.71
29	57	7	1.01	1.25	1.00	0.88	0.73
26	54	7	1.01	1.40	1.07	0.91	0.72
26	60	7	1.00	1.27	1.09	0.99	0.88
34	54	2	1.00	1.18	1.00	0.92	0.81
31	51	2	1.01	1.45	1.09	0.92	0.72
31	57	2	1.01	1.21	0.99	0.88	0.74
45	51	43	-	-	1.18	-	-
45	51	43	-	-	-	1.27	-
46	48	44	-	-	-	-	1.37

The untrimmed power peaking in drivers adjacent to the four quatrefoils is worse than in drivers adjacent to three quatrefoils not only because approximately the same amount of Am now displaces four rather than three targets, but also because of the flux asymmetry resulting from the unsymmetrical addition of Am assemblies to the host lattice. The histograms of Figure 3 show how the initially-flat radial power profile (in arbitrary GAUGE units) is centrally peaked by the addition of Am and is centrally dished by the excessive trim resulting from the addition of one 14.4S rod to each of the seven central septifoils; a single 3.2S rod added to each of these seven central septifoils is about right, although some further local trimming may be required in Gang III to suppress the displaced peak at (X45, Y51), cf. Table IV.

Table V shows power peaking in the drivers in the seven central hexes at start stage 1 after the Am has already been exposed for five target stages. The peaking is worse than at start stage 1 with fresh Am, but it can be reduced to tolerable levels by adding control rod trim, as indicated. Histograms of the radial power profile (in GAUGE units) are shown in Figure 4.

[redacted]

Table V

Four Quatrefoil Power Peaking at Start Stage 1
(Am exposed for 5 stages in 4 Q-foils near center)

M14 Driver at X	Y	In Cluster	No Am	Am, no trim	Am with one added 3.2S	Am with two added 3.2S	Am with one added 14.4S
27	45	1	1.01	1.55	1.14	0.94	0.70
27	51	1	(1.01)	1.80	1.32	1.09	0.80
30	48	1	1.01	(1.85)	1.35	1.11	0.80
32	42	3	1.01	1.36	1.08	0.94	0.75
32	48	3	1.01	1.79	(1.36)	1.14	0.87
35	45	3	1.00	1.52	1.27	1.15	0.98
28	36	4	1.00	1.19	1.02	0.94	0.81
28	42	4	1.01	1.45	1.10	0.93	0.71
31	39	4	1.00	1.24	1.01	0.90	0.75
23	45	5	1.01	1.30	1.04	0.91	0.73
26	42	5	1.01	1.57	1.21	1.03	0.80
23	39	5	1.00	1.39	1.19	1.08	0.94
22	54	6	1.00	1.25	1.06	0.97	0.83
25	51	6	1.01	1.55	1.17	0.98	0.74
22	48	6	1.01	1.23	1.01	0.89	0.74
29	57	7	1.01	1.48	1.16	1.00	0.80
26	54	7	1.01	1.75	1.33	1.12	0.86
26	60	7	1.00	1.53	1.28	1.16	0.98
34	54	2	1.00	1.34	1.12	1.01	0.86
31	51	2	1.01	1.81	1.36	1.13	0.85
31	57	2	1.01	1.39	1.11	0.98	0.80
24	60	18	-	-	-	(1.19)	-
45	51	43	-	-	-	-	(1.30)

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The change in power level of a driver adjacent to an Am assembly can also be expressed in terms of the ratio of the driver power after the target has been replaced by an Am quatrefoil to the power in that same driver before the target has been replaced. Tables VI, VII, and VIII show this "after/before" peaking in nearby drivers for two, three, and four Am quatrefoils, all normalized to the same Gang I and II average power before and after substitution. Peaking values listed in Table VI were calculated by JPROD.HERESY at two stages in the fuel cycle, with no trim; those listed in Table VII and VIII were calculated by GAUGE for two start stage 1 cases, both without trim and with the about-optimum additions of one or two 3.2S rods to each of the seven central septifoils.

Table VI

Untrimmed "After/Before" Peaking

Fuel Cycle	ML4 Driver at	2.6 kg Am in 2 Q-foils*	2.6 kg Am in 3 Q-foils**
start stage 1	X29, Y57	1.15	1.24
start stage 1	X31, Y57	1.15	1.24
start stage 1	X31, Y51	1.18	1.28
start stage 4	X29, Y57	1.07	1.14
start stage 4	X31, Y57	1.07	1.13
start stage 4	X31, Y51	1.08	1.16

*at (X30, Y54) and (X26, Y42)

**at (X30, Y54), (X24, Y48), and (X30, Y42)

[redacted]

Table VII

Start Stage 1 "After/Before" Peaking

M14 Driver at X	Y	2.6 kg fresh Am in 4 Quatrefoils*: Untrimmed	With One added 3.2S Rod
27	45	1.27	0.94
27	51	1.42	1.05
30	48	1.45	1.07
32	42	1.18	0.95
32	48	1.40	1.07
35	45	1.26	1.08
28	36	1.09	0.95
28	42	1.22	0.93
31	39	1.12	0.92
23	45	1.14	0.93
26	42	1.29	1.00
23	39	1.19	1.04
22	54	1.12	0.97
25	51	1.27	0.97
22	48	1.11	0.92
29	57	1.24	0.99
26	54	1.38	1.06
26	60	1.26	1.08
34	54	1.17	1.00
31	51	1.43	1.08
31	57	1.20	0.98

*at (X29, Y51), (X25, Y39), (X25, Y57), and (X34, Y48)

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Table VIII

Start Stage 1 "After/Before" Peaking

M14 Driver at X	Y	Am Exposed for 5 Stages in 4 Q-foils: Untrimmed	With Two Added 3.2S Rods
27	45	1.53	0.93
27	51	1.78	1.07
30	48	1.82	1.10
32	42	1.35	0.93
32	48	1.54	1.13
35	45	1.51	1.15
28	36	1.19	0.93
28	42	1.44	0.92
31	39	1.23	0.90
23	45	1.29	0.90
26	42	1.56	1.02
23	39	1.39	1.08
22	54	1.24	0.96
25	51	1.53	0.97
22	48	1.22	0.89
29	57	1.47	1.00
26	54	1.74	1.11
26	60	1.52	1.15
34	54	1.34	1.01
31	51	1.79	1.12
31	57	1.38	0.97

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5. Power Generation in Am Assemblies

Ratios of the fission power generated in an Am assembly to that generated in an adjacent driver, calculated from HERESY data by the expression

$$\frac{P_{Am}}{P_{M14}} = \left[\frac{(\text{th. abs.})_{Am}}{(\text{th. abs.})_{M14}}\right]_{HERESY} \cdot \left[\frac{(\text{total fissions/gp 4 smooth abs.})_{Am}}{(\text{total fissions/gp 4 smooth abs.})_{M14}}\right]_{DIED}$$

are listed in Table IX.

Table IX

Am Power/Driver Power

Fuel Cycle	M14 Driver at	2.6 kg Am homogenized in 2 Q-foils	2.6 kg Am homogenized in 3 Q-foils
start stage 1	X29, Y57	0.093	0.077
start stage 1	X31, Y57	0.096	0.080
start stage 1	X31, Y51	0.091	0.075
start stage 4	X29, Y57	0.150	0.114
start stage 4	X31, Y57	0.157	0.112
start stage 4	X31, Y51	0.146	0.110

For the three quatrefoil case fission power was calculated by APE as a function of Am exposure for a single quatrefoil containing (a) ^{241}Am only, and (b) half ^{241}Am from ORNL and half Am mixture from Hanford. The Am power increases with exposure because of the buildup of fissionable ^{239}Pu, ^{241}Pu, ^{242m}Am especially, ^{243}Cm, and ^{245}Cm. The power generated in the quatrefoil containing two columns of Am isotopes mixture plus two columns of ^{241}Am is greater than that in a quatrefoil containing only ^{241}Am because of the 0.3% ^{242m} initially present in the mixture. Am fission power vs. exposure is plotted in Figures 5, 6, 7, and 8 for the mixed quatrefoil (worse case), assuming a driver power of 7 MW/Mark 14 assembly and assuming that 2.6 kg Am is irradiated in a total of

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three quatrefoils for six target stages (to about 80% burnup of ^{241}Am) starting at stage 1, stage 2, stage 3, and stage 4, respectively. Table X lists the fission power in the mixed quatrefoil at the start and end of the various target stages in the Mark 14-30 cycle.

Table X

Am Fission Power (MW) for 7MW Driver
(3 Q Case: mixed Q with 2 col. mixture + 2 col. ^{241}Am)

	First Mark 14-30 Cycle				Second Mark 14-30 Cycle				Third Mark 14-30 Cycle			
Fig.	Start	Power	End	Power	Start	Power	End	Power	Start	Power	End	Power
4	1	0.16	4	1.14	1	0.50	2	0.83	-	-	-	-
5	2	0.20	4	1.07	1	0.51	3	1.03	-	-	-	-
6	3	0.24	4	1.12	1	0.55	4	1.33	-	-	-	-
7	4	0.31	4	1.25	1	0.60	4	1.24	1	0.52	1	0.70

The worst situation with respect to heat removal from the quatrefoil arises at the end of stage 4 when the irradiation is started at stage 3 of the previous fuel cycle (Figure 6). Here the Am fission power is 1.33 MW, which is increased to a sensible (flow·ΔT) power of 1.63 MW by including γ-heating*. This power exceeds the level taken by Reactor Engineering[6] as assuring (to allow for uncertainties in the calculations) that the quatrefoil will not operate at its limits and control reactor power.

For this reason, it was decided[5] to reduce the power per Am quatrefoil by irradiating the 2.6 kg Am in four quatrefoils with 9-foot columns rather than in three quatrefoils with 12-foot columns. A further reason for this change lay in the uncertainty in the actual amount of Am available for irradiation: while ORNL shipped about the expected** 2 kg ^{241}Am, the several batches of AmO_2 totalling 793.9 gm received from Hanford were stated to contain 631.7 gm mixed Am isotopes, rather than the 600 gm expected

*Assuming a γ escape probability of 0.73, that fission γ's = 7% of fission power, that all of n,γ energy is γ, and that the typical mass defect per neutron = 6 Mev - courtesy of J. A. Smith.

**According to the ORNL isotopes shipping documents, in two shipments totalling 2000.9 gm ^{241}Am (asserted to be in the form of 2326.3 gm oxide, theoretically equivalent to 2037.8 gm ^{241}Am - again, more uncertainty!)

[redacted]

by SRP. Thus, because the quatrefoil power was already uncomfortably high, and because the weight of Am actually present in the quatrefoils might exceed what had been assumed, it was deemed prudent to irradiate the Am in four rather than three quatrefoils.

Power calculations were repeated for the four-quatrefoil case using the GAUGE code. Table XI shows the fission power and the sensible power generated in each of the four Am quatrefoils, assuming a flat zone average driver power of 7 MW. The Am power is a minimum at start stage 1; it rises to a maximum at end stage 4, starting from stage 3 of the previous fuel cycle.

Table XI

Power Generation in Four Am Quatrefoils for 7 MW Driver

Am Q-foil at	start 1, untrimmed fission power	start 1, untrimmed sensible power	end 4, untrimmed fission power	end 4, untrimmed sensible power	end 4, trimmed fission power	end 4, trimmed sensible power
X29, Y51	0.21 MW	0.24 MW	1.50 MW	1.70 MW	1.06 MW	1.26 MW
X34, Y48	0.07	0.09	1.12	1.37	0.89	1.14
X25, Y39	0.06	0.08	1.10	1.35	0.88	1.13
X24, Y57	0.07	0.09	1.12	1.37	0.89	1.14

The highest Am power is generated in the most nearly central quatrefoil (X29, Y51) which contains the mixture of Am isotopes. The power is higher there than in the other three quatrefoils because of the fissionable ^{242m}Am initially present, and because the replacement of targets by quatrefoils causes considerable power peaking in the center of the reactor. This peaking can be almost totally flattened by adding a single 3.2S control rod to each of the seven central septifoils (the trimmed case in Table XI), with the result that although the quatrefoil at (X29, Y51) still operates at a higher power than the other three, its total flow $\cdot \Delta T$ power of 1.26 MW is now within acceptable limits.(6)

[redacted]

6. Production of ^{238}Pu

All production data were computed on the basis of an innage factor of 0.8, i.e., actual operating flux levels were reduced 20% to provide realistic decay rates for short-lived nuclides.

The weight of total ^{238}Pu, i.e., gms $^{238}Pu + \left(\frac{238}{242}\right)$ (gms ^{242}Cm) produced after irradiation for six target stages is listed in Table XII.

Table XII

Production for Six Target Stages

Fuel Cycle	Total "^{238}Pu" (for long cooling) 2 Q-foils	Total "^{238}Pu" (for long cooling) 3 Q-foils	^{252}Cf Target Material (^{243}Am + ^{244}Cm + ^{245}Cm) 2 Q-foils	^{252}Cf Target Material (^{243}Am + ^{244}Cm + ^{245}Cm) 3 Q-foils
initially	0 gm	0 gm	133 gm	133 gm
start at stage 1	1021	1070	222	236
start at stage 2	1012	1064	219	234
start at stage 3	1024	1067	225	240
start at stage 4	1030	1064	226	241

Irradiation of Am in three rather than two quatrefoils produces 4% more ^{238}Pu. Production is hardly affected by the point in the fuel cycle at which the irradiation is started.

Table XIII shows the isotopic composition of the Am before and after irradiation for six target stages, after starting at stage 3.

[redacted]

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Table XIII

Initial and Final Compositions

Isotope	Initial Weight	Composition of "Am" after Six Target Stages in 2 Q-foils	in 3 Q-foils
^{238}Pu	0 gm	335 gm	335 gm
^{239}Pu	0	82	96
^{240}Pu	0	18	26
^{241}Pu	0	5	7
^{242}Pu	0	197	210
^{241}Am	2465	618	443
^{242m}Am	2	12	9
^{243}Am	133	169	177
^{242}Cm	0	700	744
^{244}Cm	0	55	62
^{245}Cm	0	1	1
fission products*	0	407	490
Total	2600	2600	2600

*includes traces of ^{242}Am, ^{243}Cm, ^{246}Cm ... ^{248}Cm

82% of the ^{241}Am is burned up if the Am is irradiated in three quatrefoils, vs. 75% burnup for two quatrefoils, because of the lower self-shielding in the former case.

Relative atom concentrations as functions of Am exposure are plotted in Figure 9 for pure ^{241}Am in 2½ quatrefoils (240 slugs), and in Figure 10 for the Am mixture in ½ quatrefoil (48 slugs). The only significant difference is the higher concentration of ^{243}Am and ^{244}Cm in the latter case; the concentrations of ^{238}Pu and ^{242}Cm are virtually the same for both cases. The concentrations of ^{238}Pu and ^{242}Cm as functions of exposure have levelled off, and

nothing is to be gained by pushing the irradiation past six target stages. In fact, the exposure might well be terminated after five target stages, with inconsequential loss of production, if the quatrefoil power turns out to be limiting total reactor power (cf. Section 5).

Production figures for six target stages (starting at stage 3) for the more favorable three quatrefoil case are listed in Table XIV, broken down into detailed yields from (a) 48 slugs of Am mixture, and (b) 240 slugs of ^{241}Am.

Table XIV

Production in Three Quatrefoils

Isotope	Mixed Am in ½ Q-foil	^{241}Am in 2½ Q-foils	Total
^{238}Pu	63 gm	272 gm	335 gm
^{239}Pu	18	78	96
^{240}Pu	5	21	26
^{241}Pu	1	6	7
^{242}Pu	40	170	210
^{241}Am	84	359	443
^{242m}Am	2	7	9
^{243}Am	108	69	177
^{242}Cm	140	604	744
^{244}Cm	42	20	62
^{245}Cm	0.6	0.3	1
Total "^{238}Pu"	201	866	1067
^{252}Cf Target Material	151	89	240

Figure 11 shows the maximum product purity for long cooling, i.e., (wt. $^{238}Pu + \frac{238}{242}$. wt. ^{242}Cm)/(wt. all Pu isotopes + $\frac{238}{242}$. wt. ^{242}Cm), as a function of exposure. Figure 12 shows the minimum product purity, i.e., (wt. ^{238}Pu)/(wt. all Pu isotopes), at discharge (no cooling) as a function of exposure.

[redacted]

The production calculations were not repeated for the four quatrefoil case because the effects of uncertainties in pertinent cross sections are felt to be large compared to the difference that would result from explicit consideration of the change in relative flux. (Note, from Figures 9 and 10, that contents vary slowly with exposure toward the endpoint of the irradiation.) Table XIV should be taken as the estimate of contents at the end of the irradiation.

DR/vpb

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2. F. J. McCrosson, Revised HAMMER Cross Section Library, Memorandum, May 7, 1969.

3. R. P. Christman, HAMMER Cross Section Library Modifications, Memorandum, October 18, 1967.

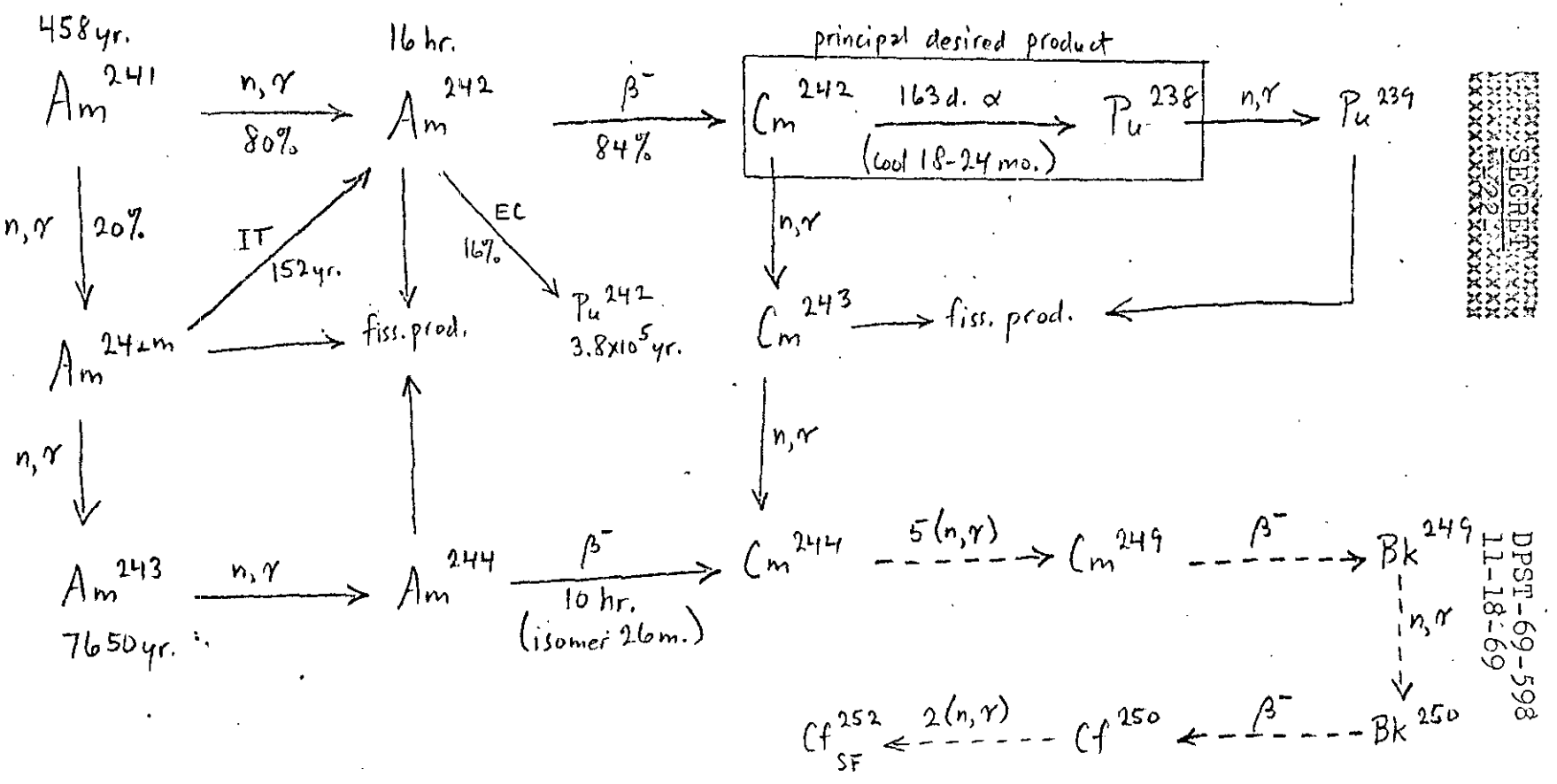
4. W. R. Cornman, Changes in APE Built-in Nuclear Data, Memorandum, November 8, 1968.

5. D. Randall, J. A. Smith, Change in Am Irradiation Plans, DPST-69-554, October 13, 1969.

6. R.C. Thornberry, Target Quatrefoil Assembly for E-D, Memorandum, August 29, 1969. Memorandum from J. R. Taylor to H. E. Wingo (October 17, 1969).

Figure 1.

Irradiation Scheme



(subsequent high-flux irradiation shown by dashed lines)

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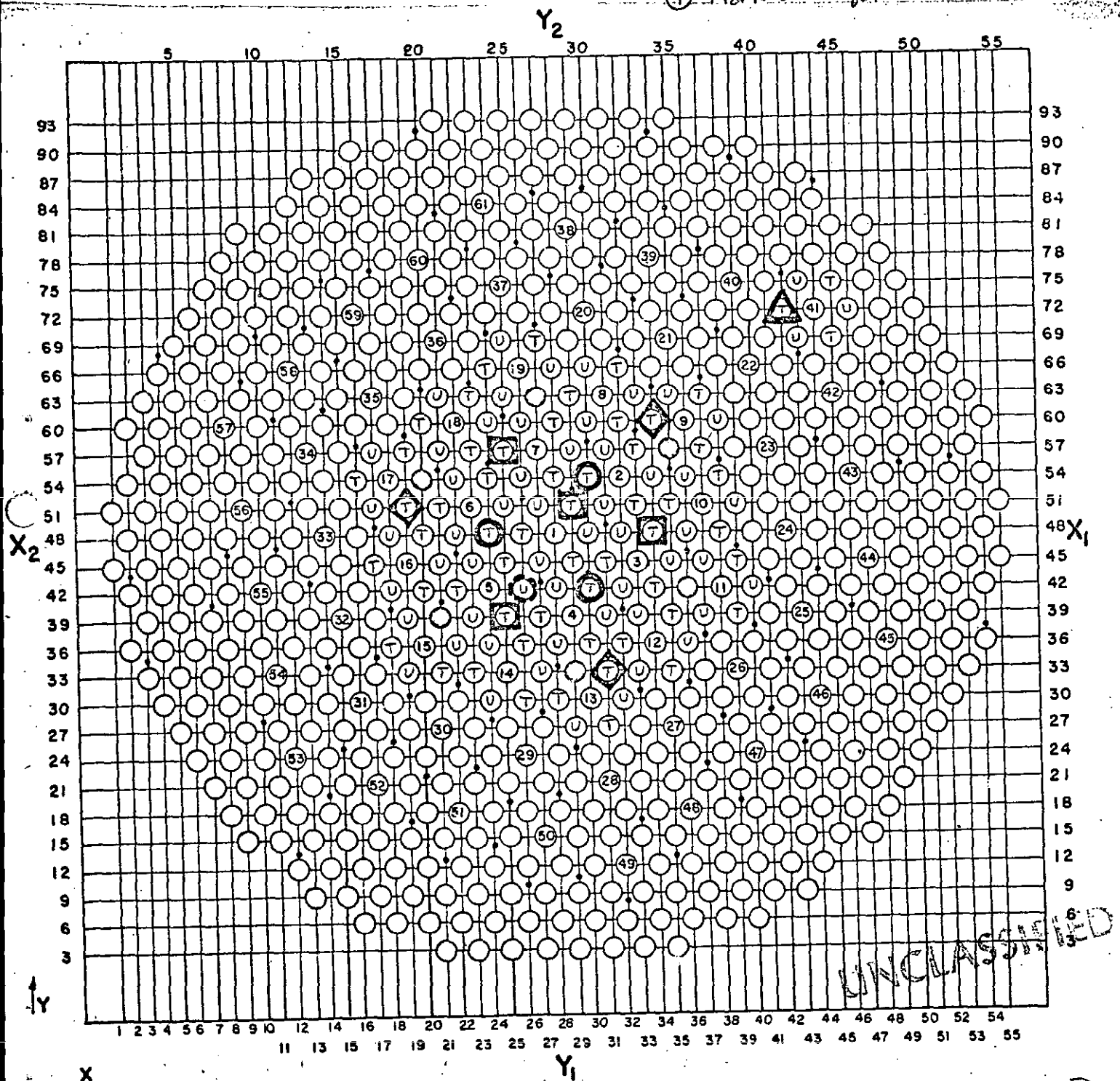
Figure 2.

Location of Am Quatrefoils

Ⓤ Mark 14 driver

Ⓣ Mark 30 target



[redacted]

□ currently proposed location of four quatrefoils

◇ recently proposed location of three quatrefoils next to sparjets

○ ◌ previously proposed location of two or three quatrefoils near center

△ originally proposed location of single quatrefoil with 600 gm. Am

} with 2.6 kg. Am

Figure 3. [redacted] DPST-69-598
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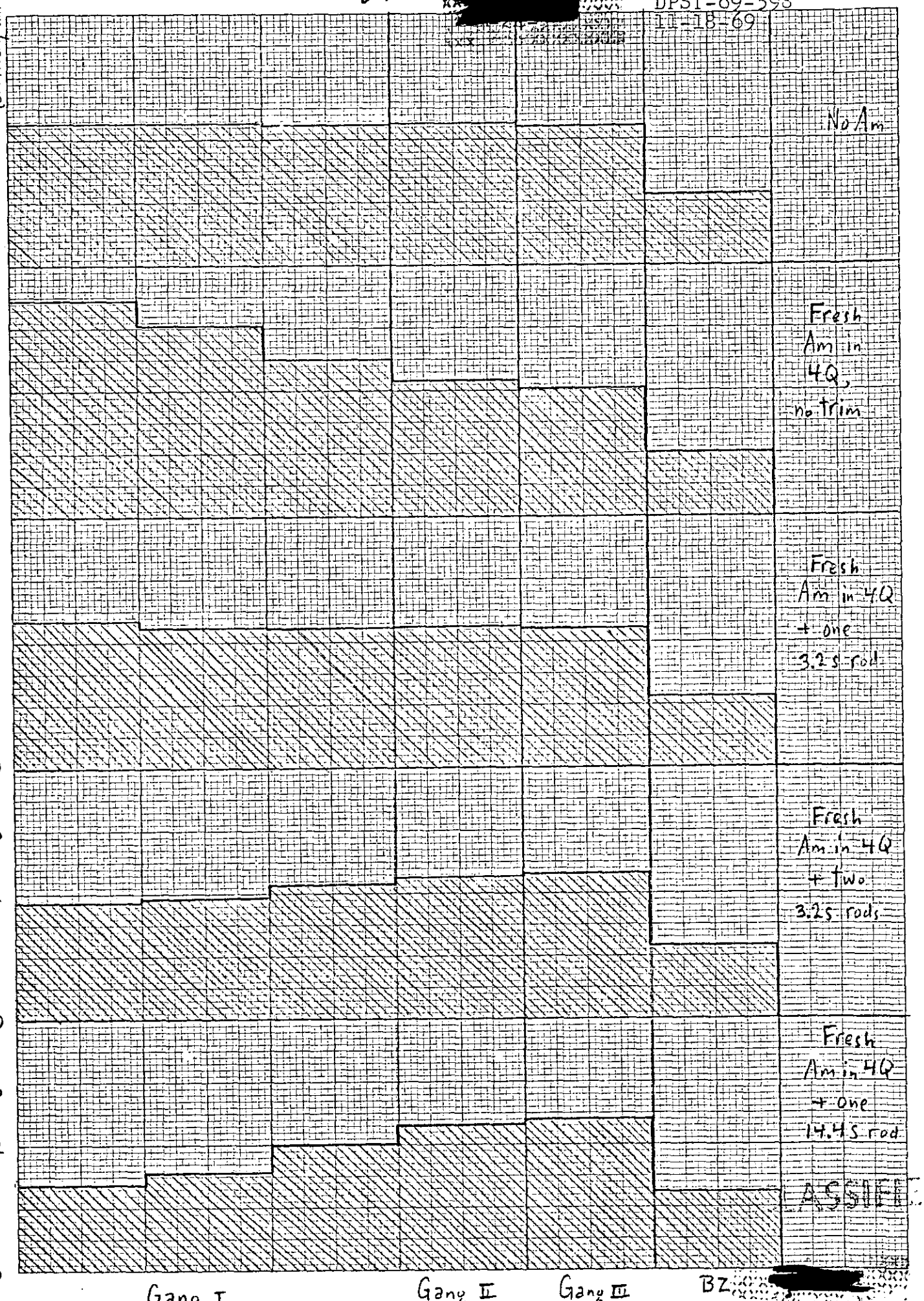

Figure 4. [redacted] DPST-69-598
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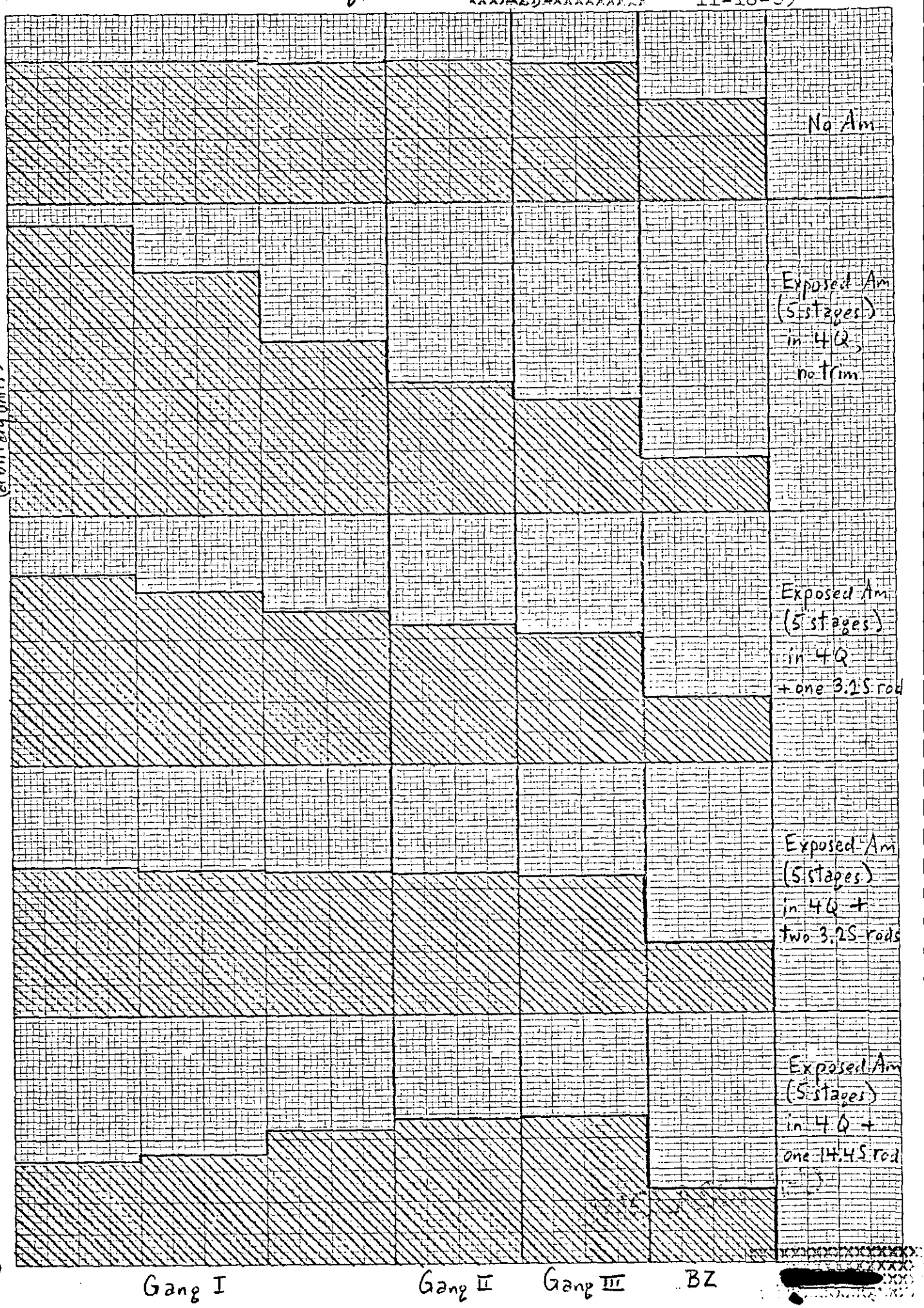

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Figure 5.

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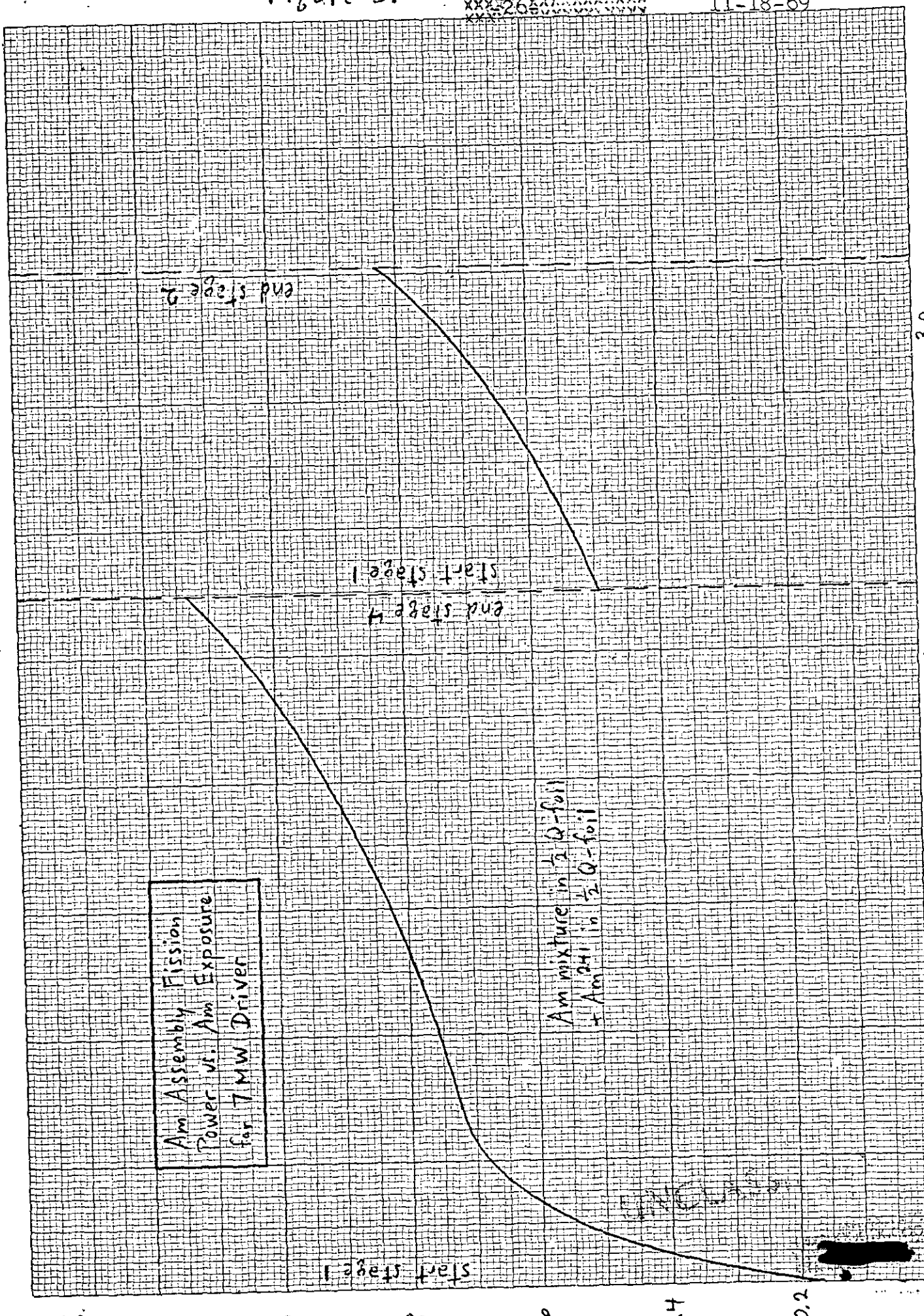

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Figure 6.

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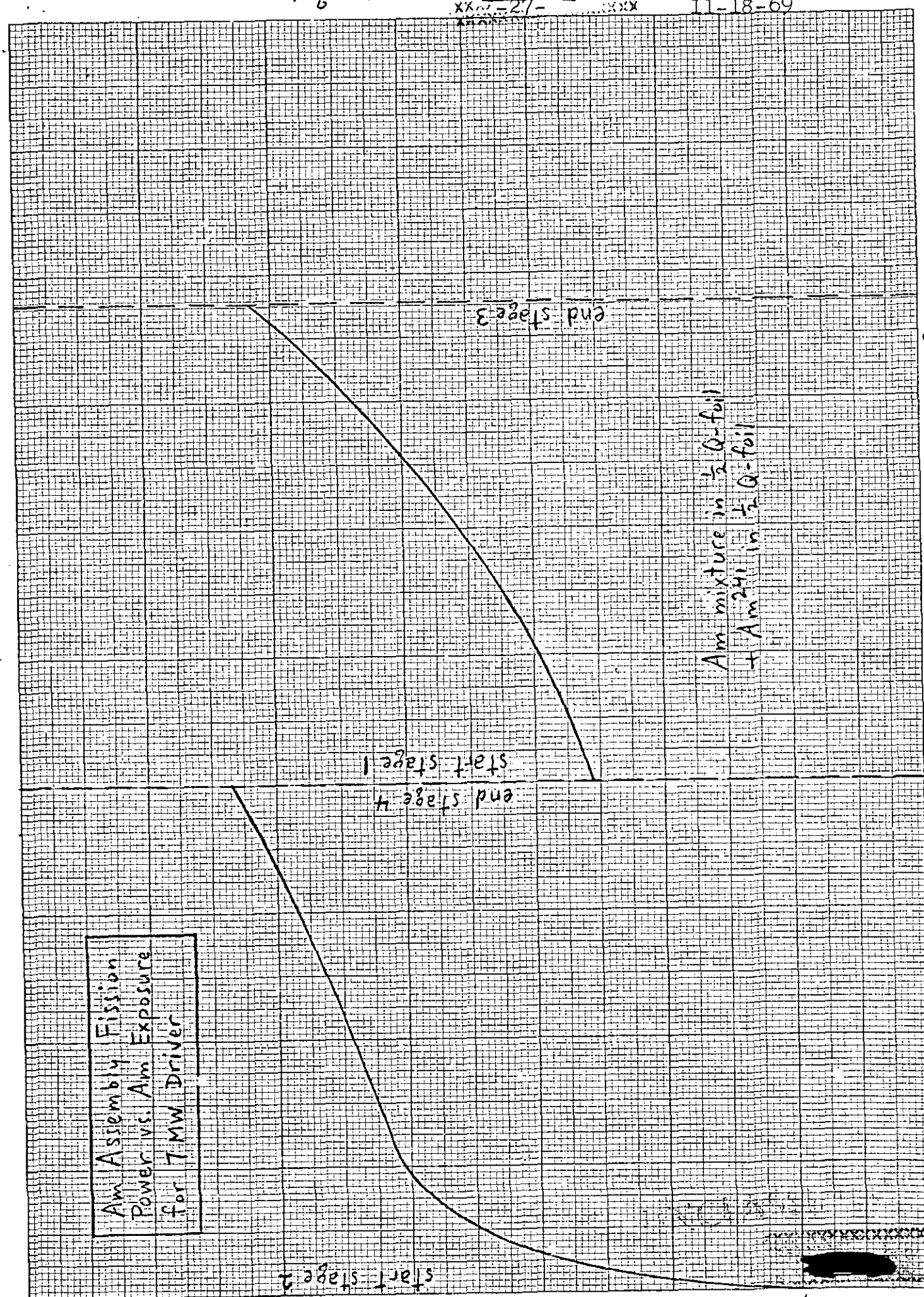

Figure 7. [redacted]

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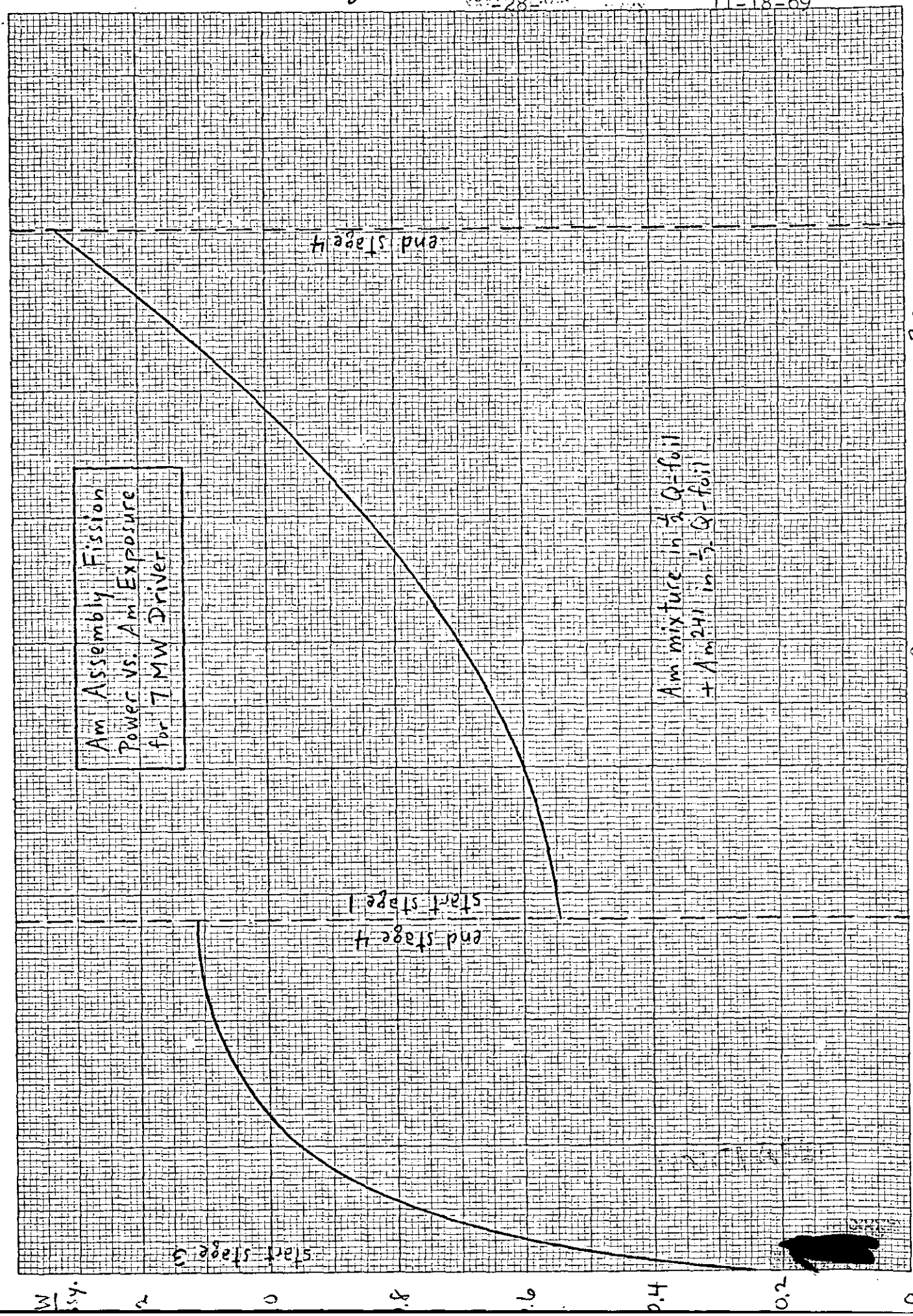

Figure 8.

[redacted] DPST-69-598
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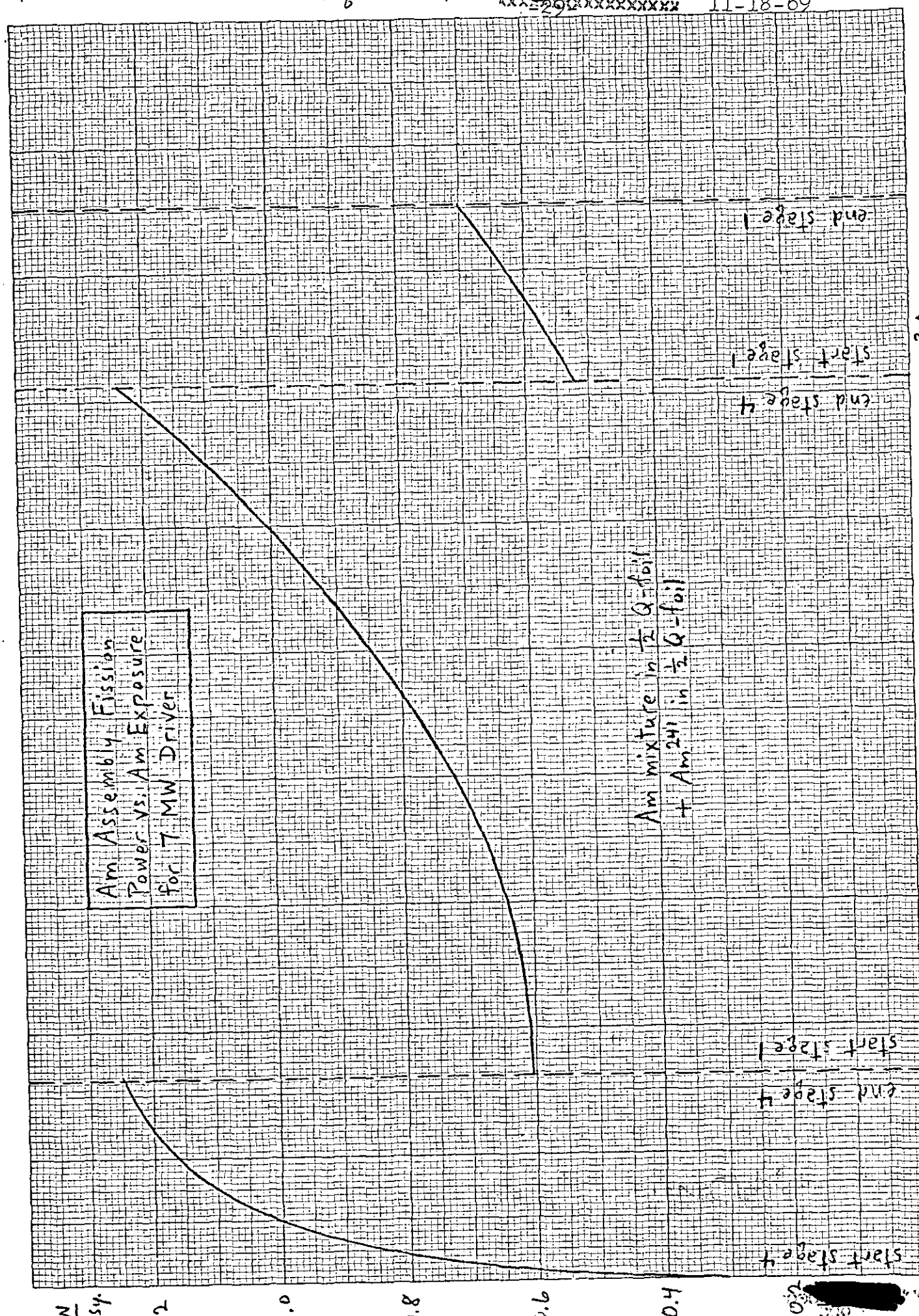

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Figure 9.

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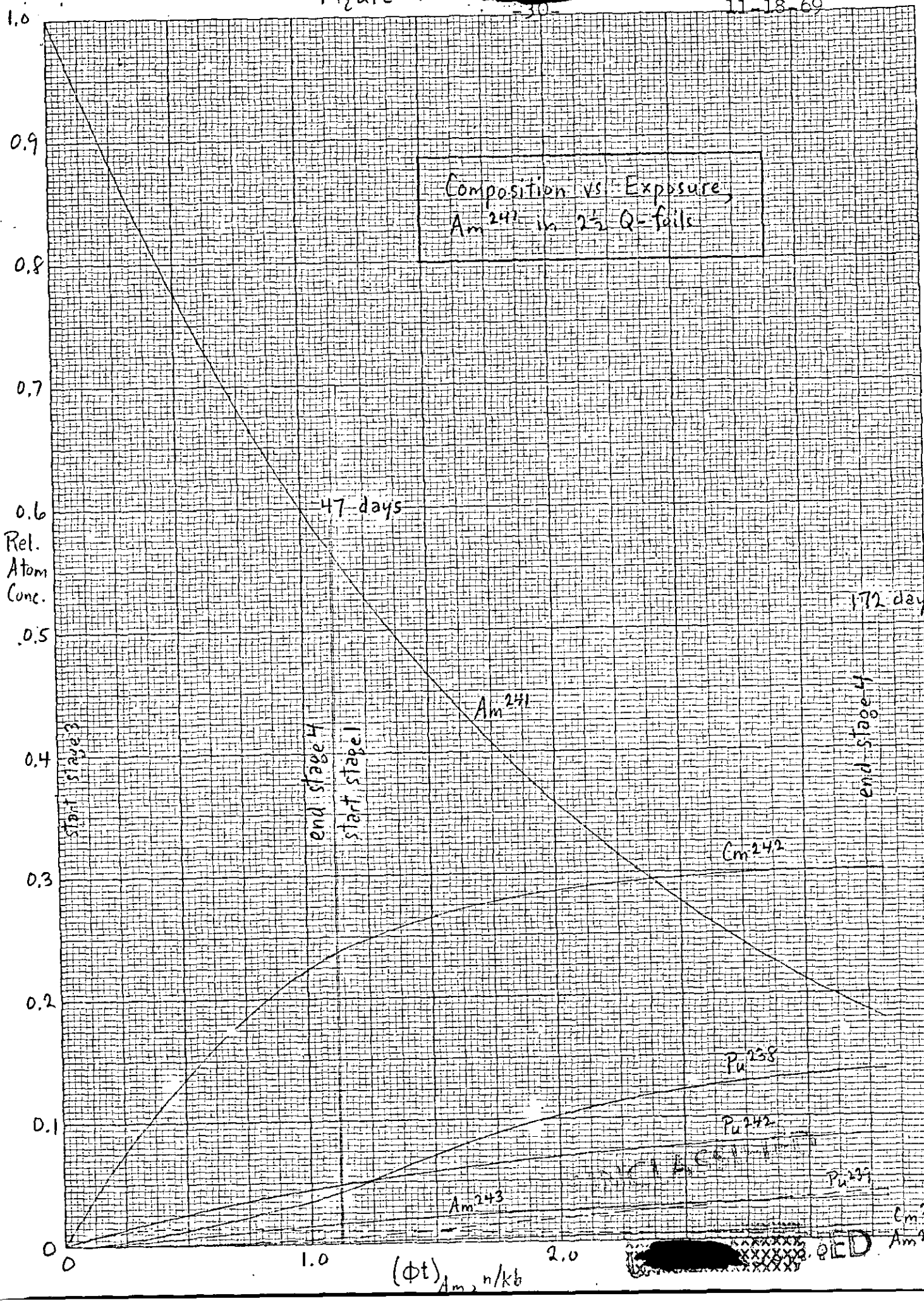

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Figure 10. [redacted]-31 [redacted]

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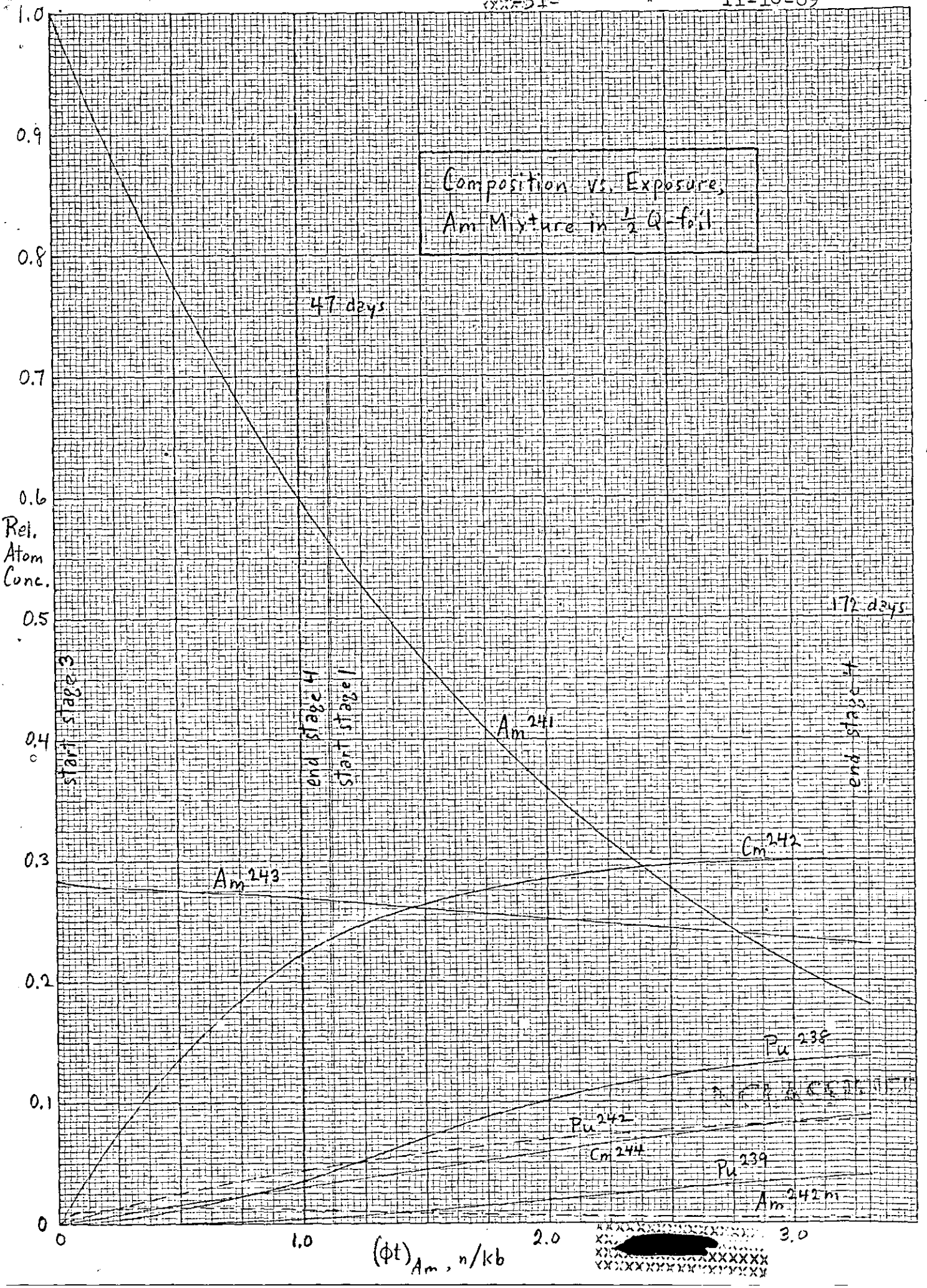

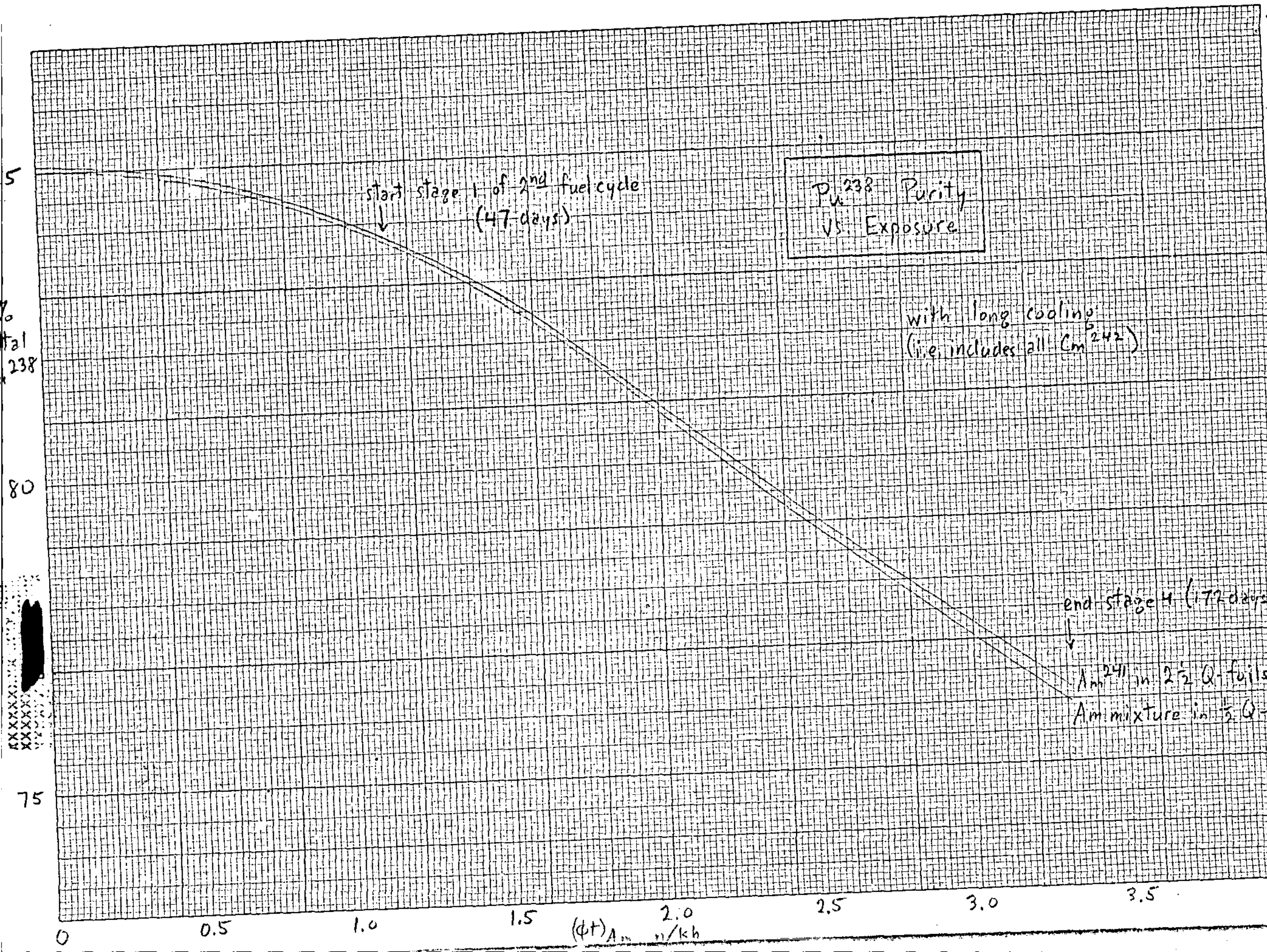

Figure 11.

[redacted]

[redacted]

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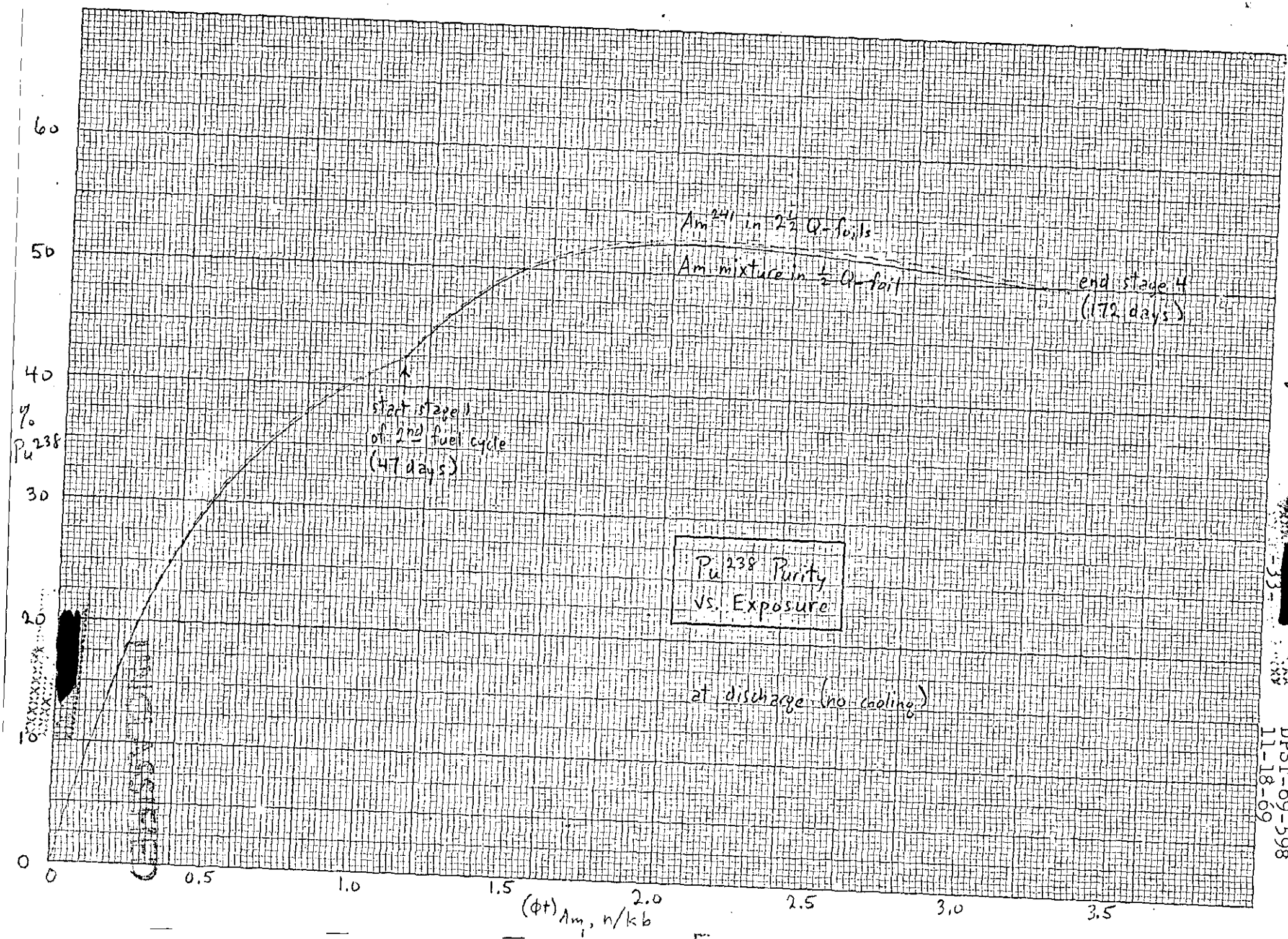

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